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This report was developed under an SBIR award for Solicitation topic # N08-072.

The present report summarizes the Phase 1 Option work of TrellisWare Technologies, Inc. (TrellisWare) in the development of an optimized coded protocol to combat the deep fades caused by scintillation in free-space optical (FSO) communication links

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Phase 1 Option Final Report

Optimized Coding and Protocols for FSO Communications Links

TrellisWare Technologies, Inc.

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Optimized Coding and Protocols for FSO Communications Links
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Executive Summary

This report summarizes the progress made by TrellisWare Technologies, Inc. ("TrellisWare") during **Phase-I Option,** toward the development of an optimized coded-protocol for free-space optical (FSO) communication links**.**

For Phase-I, TrellisWare proposed the joint use of coding and protocol ("coded-protocol") to mitigate the scintillation induced fading on FSO communication links. The proposed coded-protocol would adapt the code-rate to match prevalent channel conditions seamlessly using feedback from the receive side.

The Phase-I study involved the careful development of a system simulation that included models for an FSO transmitter with code-rate adaptation and an FSO receiver with code-rate estimation capability. In order to test the utility of the proposed approach, TrellisWare also developed FSO channel models that could be configured with scintillation parameters. At the end of the Phase-I study we reported the successful completion of a coded-protocol framework combining a Hybrid Automatic Repeat reQuest (H-ARQ) protocol driven by TrellisWare's modern Flexible Low-Density Parity-Check (F-LDPC) code family. The expected throughput/latency performance of the proposed system was also reported for a wide range of scenarios.

Several simplifying assumptions had been made in Phase-I to expedite algorithm development and testing. One of these was the assumption that the feedback channel was error-free (but not delay-free) with the understanding that the performance with the error-free assumption would provide an upper bound on achievable performance in practice. Moreover, the proposed system model still needed to be tested with channel data collected from FSO testing facilities. TrellisWare proposed a plan to study these details in Phase-I Option.

In our first progress report in Phase-I Option, we reported the impact of errors in the feedback channel on system performance - a time-out mechanism was introduced for automatic packet retransmission for continually corrupt feedback. We had also described the expected coded reliability of the feedback channel in reference to the forward channel. The final part of the Phase-I Option work, summarized in this report, focused on

(1) structures for data and feedback packets

(2) calibration of packet time-out parameters

(3) simulated performance of the protocol using channel data sets provided by the NRL

(4) a comparison of system performance using NRL channel data sets and that using TrellisWare channel models configured with turbulence parameters derived from NRL channel data.

A. TrellisWare's coded-protocol for fading mitigation

Figure 1 shows a functional block diagram of the proposed system, which consists of the FSO TX, the forward channel, the FSO RX and the reverse channel. Using smart feedback information, the protocol responds to varying channel conditions by adapting the code-rate. Due to the flexibility of the F-LDPC, information is provided in an incremental fashion on packets that failed to decode, resulting in high bandwidth utilization. At any given time, the protocol coordinates multiple on-air data packets on the forward link and multiple feedback packets on the reverse link.

For more details on system operation, please refer to our first and second progress reports for the Phase-I study [2, 3].
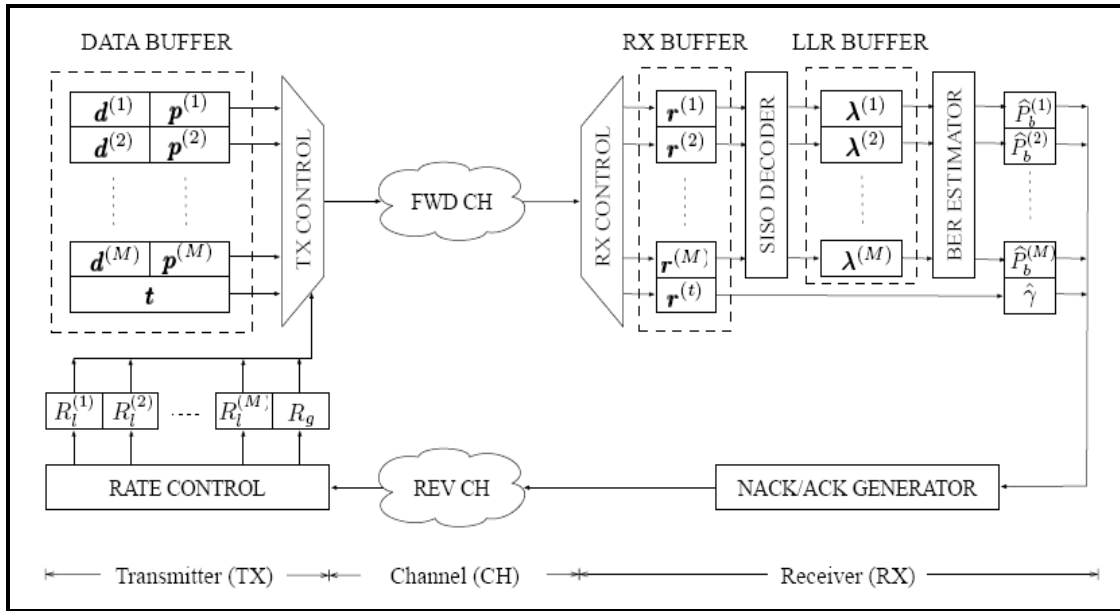

Figure 1: Functional block diagram of the proposed system.

B. Summary of work on detailed protocol specification

TrellisWare implemented additional aspects of the protocol specification, including the specification of packet structure for the forward (data) and reverse (feedback) channels, as well as the packet time-out mechanism.

B1. Packet structures

The packet structure for the forward channel is displayed in Figure 2. A data packet starts with a sequence (TR) of training bits with good correlation properties (e.g., a Gold sequence). This sequence is used to acquire the timing of the packet as well as to compute decoder scaling factors. The training sequence is followed by the packet header (HEADER), which contains information about the data transmission; including code-rate as well as packet ID information. The header information is repeated, appended with a sequence of cyclic-redundancy-check (CRC) bits and encoded using a low-rate F-LDPC. The header is followed by the payload (PAYLOAD), which contains a full or a partial F-LDPC codeword resulting from a CRC'd message word. **The overhead due to non-payload bits is expected to be less than 1 percent on average.**

packet ID,
encoding information,
CRC

full/partial codeword,
CRC

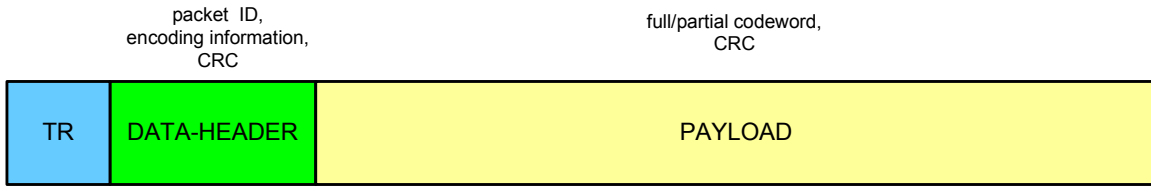| TR	DATA-HEADER	PAYLOAD

Figure 2. Structure of the data packet. Displayed lengths are in channel bits.

As soon as a data packet is transmitted, the corresponding packet status is set to BUSY, pending feedback from the receiver.

If the receiver detects a data packet, it extracts timing information using the training symbols, and starts processing the header. The received header signal is decoded and checked for CRC consistency. If the header-CRC passes, the header information is considered correct, and channel metrics (i.e. log-likelihood ratios or LLRs) are computed using the received payload bit values. The channel metrics are written into the corresponding LLR buffer, determined by the packet ID. If the payload-CRC passes, an ACK is issued and a suggested encoding rate R_ACK is computed. If the payload CRC does not pass, a NACK is issued and a suggested encoding rate R_NAK is computed.

packet ID,
ACK/NAK
suggested code-rates,
CRC
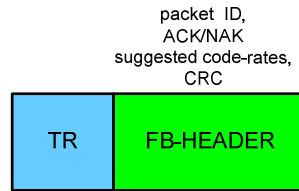
TR	FB-HEADER

Figure 3. Structure of the feedback packet. Displayed lengths are in channel bits.

If an ACK or a NACK is issued, the receiver transmits a feedback packet on the reverse channel. The feedback packet (Figure 3) consists of the same sequence of training bits as the data packet, followed by a feedback header (FB-HEADER) consisting of the packet ID, ACK/NACK information and suggested code rate. The feedback header is repeated, appended with a sequence of CRC bits and coded using a low-rate F-LDPC. The bandwidth penalty due to feedback messages is also expected to be less than 1 percent on average.

B2. Packet time-out

If the data packet is not detected, or if the header-CRC does not pass, the receiver does not issue any feedback, and the transmit side will issue a **time-out** on the particular packet after a time-out period, and move the packet status to "timed-out". The time-out period depends on the link distance, stack size and traffic requirements; however, it should not be shorter than the minimum latency that a packet can experience. When channel conditions are favorable, sequence of packets are ACK'd and feedback is decoded successfully at the transmit side. Under these conditions, worst-case T_{ACK} (measured from the time a packet is admitted to the data buffer to the time an ACK is received) can be bounded by

$$T_{ACK,\max} \geq (T_{ENC} + T_{DEC}) + T_{round\_trip}$$

where T_{ENC} and T_{DEC} are encoder latency and decoder latency per block and T_{round_trip} is the round-trip signal propagation time. In practice, a busy packet is timed out if the number of valid feedback messages for packets other than the packet in question exceeds a certain threshold. The threshold is typically set to twice the stack size. Once the packet time-out period is exhausted, a packet with a full-codeword payload (using the current encoder-rate) is transmitted.

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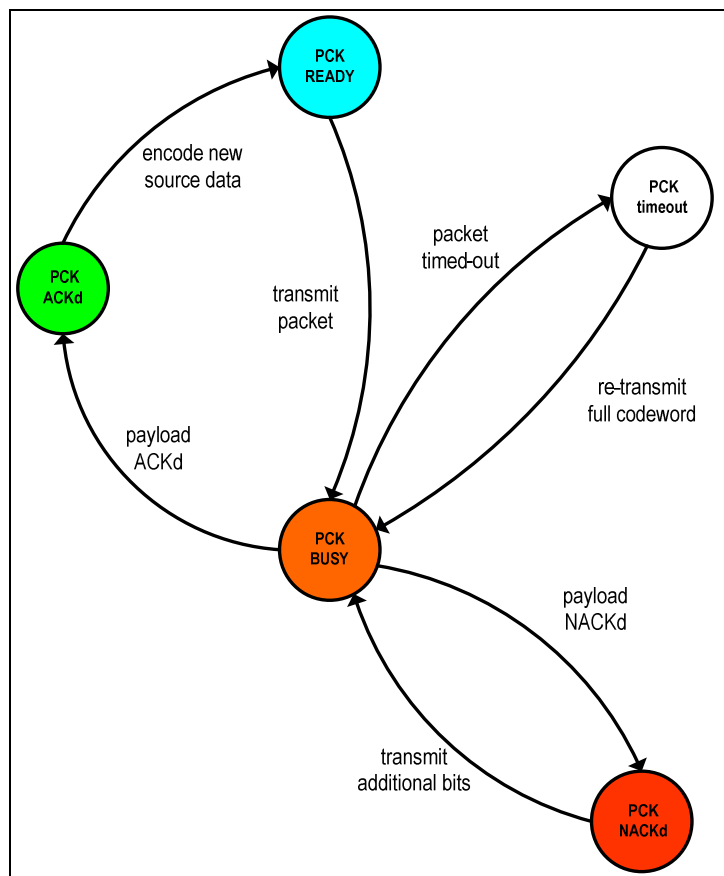**PHASE-I OPTION FINAL REPORT**

Figure 4. Packet state diagram.

B2. Decoding of feedback messages

The transmitter acquires feedback packets using the training bits, and then runs the feedback payload decoder. If the feedback header CRC passes upon decoding[1], the feedback information is considered correct, and the transmitter uses the ACK/NAK information extracted to update the transmitter parameters, including the global encoding rate used for new data packets.

If the feedback packet indicates an ACK, the corresponding memory location in the data buffer is cleared and packet status is moved from BUSY to ACKd. If new data is available from the source, it is encoded with a low-rate F-LDPC, and the full codeword is written onto the data buffer. The global encoding rate is used to make the payload bits of a new packet (Figure 2). Packet status is moved from ACKd to READY (Figure 4).

If the feedback packet indicates a NACK, a data payload is made containing additional codeword bits as indicated by the suggested code rates extracted from the feedback header. The packet status is then moved from BUSY to NACKd and back to BUSY once the additional packet bits are transmitted. If the packet has been NACK'd too many times, it may be retransmitted in full using the lowest code rate.

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[1] If the feedback header CRC does not pass, the feedback is discarded and the packet will time-out eventually.

C. Protocol performance using NRL channel data

The NRL provided three channel data sets for performance evaluation: (1) Low-turbulence retroreflected signal from a 170m distance (total signal travel distance is 340m), (2) medium-turbulence direct signal on a 1750m-link and (3) a high-turbulence retroreflected signal from a 170m distance. A channel data set is a list of pairs (V(t), t), where t is the time in seconds, and V(t) is the electrical voltage quantity observed at time t. In order to obtain intensity values on a symbol-by-symbol basis, the set of voltages is **interpolated at the channel rate R_{ch} = 2 Gbps[2]** to obtain {V(k/R_{ch}), k=1,2….}. In the absence of receiver noise, the received signal value corresponding to the kth channel bit c_k, is then given by

$$r_k = \begin{cases} V\left(\dfrac{k}{R_{ch}}\right) + w_k, & c_k = 0 \\ w_k, & c_k = 1 \end{cases}$$

where {w_k} are independent and identically distributed Gaussian samples mean zero and variance σ^2.

There is negligible variation of voltage within a 50 usec segment in all data sets. At 2 Gbps, the longest packet is approximately 16 usec long, therefore a transmit packet often experiences a single voltage value (in the absence of noise). The instantaneous (i.e. per-packet) received signal-to-noise ratio is therefore given by $SNR_{packet} = V^2/\sigma^2$, whereas the average signal-to-noise ratio is the temporal average, $SNR_{avg} = <V^2>/\sigma^2$.

The extent to which SNR*$_{packet}$* varies around its mean is criticial in terms of achievable packet latency. If the SNR*$_{packet}$* drops below a critical value, decoding becomes unreliable; in fact, the packet may not even be detectable. This event is called *outage*, and the outage duration adds to the packet latency. The SNR threshold below which the system goes into outage is determined by the minimum code-rate as well as the digital sensitivity of the receiver.

C1. Low-turbulence retroreflected signal

Figure 5 displays the fluctuation of the received signal intensity with respect to its average value for the low-turbulence signal for the first second of transmission. Figure 6 displays the cumulative distribution function (cdf) of the fluctuation for the entire data set (30 sec.). Less than 1 percent of the packets experience an SNR that is more than 4 dB below the average SNR.

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[2] For Phase-II, TrellisWare proposed a hardware implementation based on a channel bit rate of 2 Gbps.
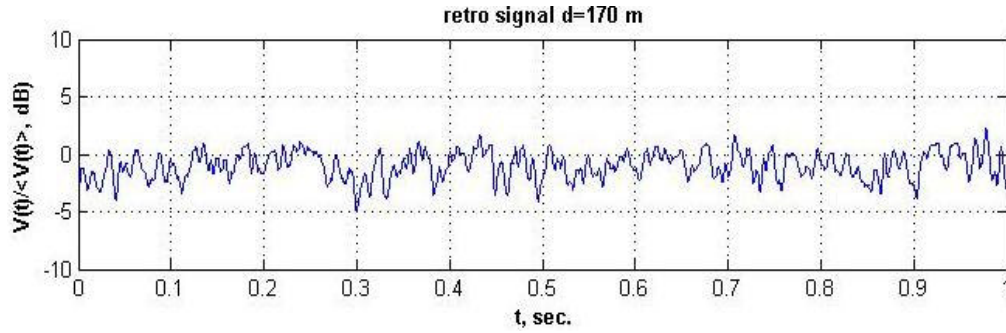
PHASE-I OPTION FINAL REPORT

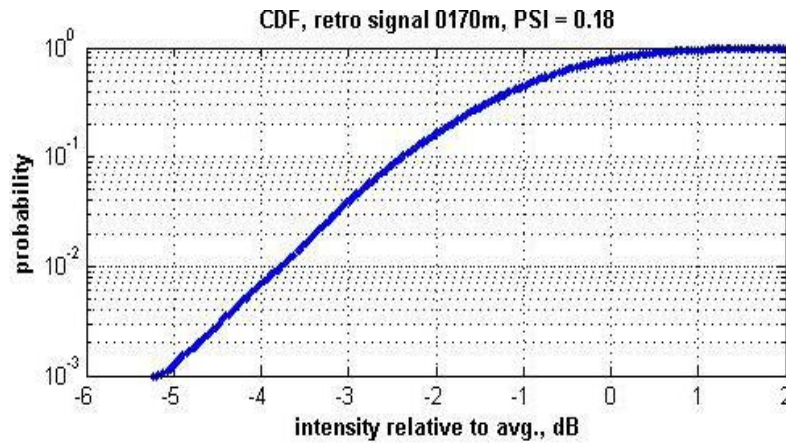**Figure 5. Fluctuation of the low-turbulence signal.**

Figure 6. Cumulative distribution function of the signal fluctuation (low-turbulence signal)

Table 1.
Simulated performance of the coded-protocol over the low-turbulence channel, R_{ch} = 2 Gbps.

	retrosignal 0170m	
	experiment 1	experiment 2
Avg receive snr, dB	3	10
Throughput, Mbps	530	1260
Avg latency, msec	0.16	0.06
Max latency, msec	9	1.2

)

Table 1 lists the achieved performance over six million ACKed packets using the low-turbulence channel data set for two different receive SNR values. At relatively low average SNR, SNR_{avg} = 3 dB, approximately 3 percent of the packets experience $SNR_{packet} < 0$ dB[3], but the protocol still delivers over 500 Mbps with an average packet latency of 160 usec. At relatively high SNR_{avg} (10 dB), the protocol achieves over **1.25 Gbps error-free throughput** with an **average packet latency of 60 usec.**

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[3] The – 3dB point corresponds 0.03 (3 percent) on the cdf. If SNR_{avg} = 3 dB, then the probability that SNR_{packet} is greater than $SNR_{avg} – 3$ dB is at least 97 percent.

C2. Medium-turbulence direct signal

Figure 7 displays the fluctuation of the received signal intensity with respect to its average value for the medium-turbulence signal for the first second of transmission. Figure 8 displays the cdf of the fluctuation for the entire data set. Approximately 1 percent of the time, the packets experience an SNR that is **more than 28 dB below the average SNR**. We assumed an average receive SNR of 30 dB.
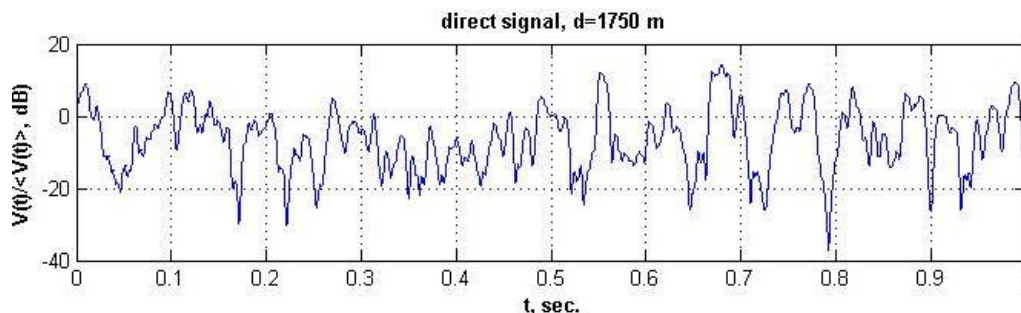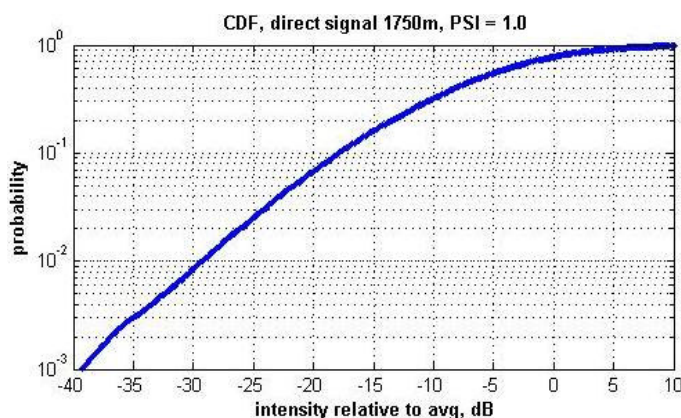

Figure 7. Fluctuation of the medium-turbulence signal

Figure 8. Cumulative distribution function of the signal fluctuation (medium-turbulence signal)

Table 2.
Simulated performance of the coded-protocol over the medium-turbulence channel, R_{ch} = 2 Gbps.

	directsignal 1750m
Avg receive snr, dB	30
Throughput, Mbps	610
Avg latency, msec	0.3
Max latency, msec	4.4

)

Table 1Table 2 lists the achieved performance over six million ACKed packets using the medium-turbulence channel data set for SNR$_{avg}$ = 30 dB. The protocol achieves approximately **0.61 Gbps error-**

free throughput with an **average packet latency of 0.3 msec.**

C3. High-turbulence retroreflected signal

Figure 9 displays the fluctuation of the received signal intensity with respect to its average value for the high turbulence signal for the first second of transmission. Figure 9 displays cdf of the fluctuation for the entire data set (30 sec.). Again, due to the severity of the fades, an average SNR of 30 dB is assumed.
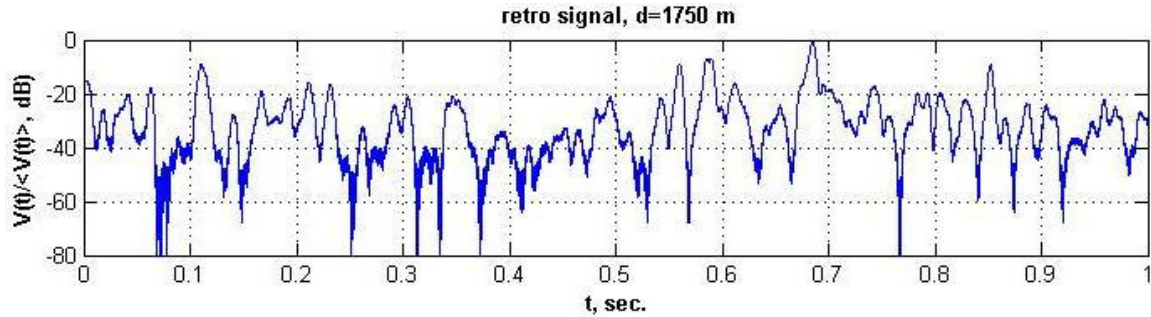

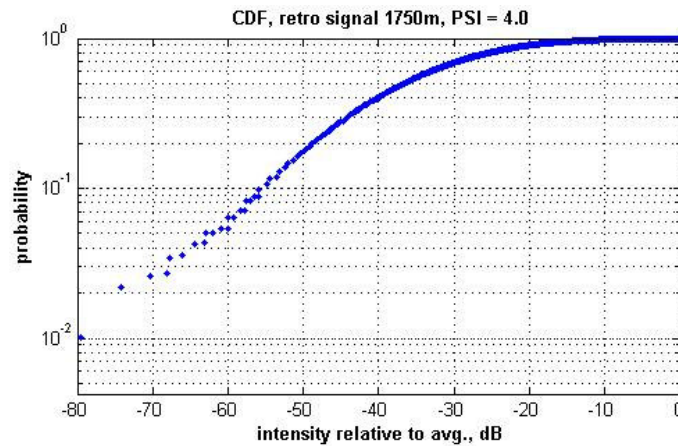**Figure 9. Fluctuation of the high-turbulence signal.**

Figure 10. Cumulative distribution function of the signal fluctuation (high-turbulence signal).

Table 3. Simulated performance of the coded-protocol over the high-turbulence channel, R_{ch} = 2 Gbps.

	retrosignal 1750m
Avg receive snr, dB	30
Throughput, Mbps	98
Avg latency, msec	1.5
Max latency, msec	88

Table 3 lists the achieved performance over one million ACKed packets using the high-turbulence channel data set for SNR_{avg} = 30 dB. The protocol achieves approximately 98 **Mbps error-free throughput** with an **average packet latency of 1.5 msec.**

D. TrellisWare's FSO channel models with NRL channel data parameters

A final experiment was conducted to compare, in terms of end-to-end system performance, NRL channel data and an equivalent renewal-based FSO channel model developed in Phase 1. In order to generate a model equivalent to the NRL channel data, the NRL data was first analyzed to determine the distribution of the signal intensity, I, quantized to bins of width 0.125 dB. A second pass was then made to determine the mean hold-time, $T_{avg}(I)$, per (quantized) intensity state. Figure 11 displays the scatter diagram of quantized intensity states vs. average hold-time per intensity state for the medium-turbulence data set.
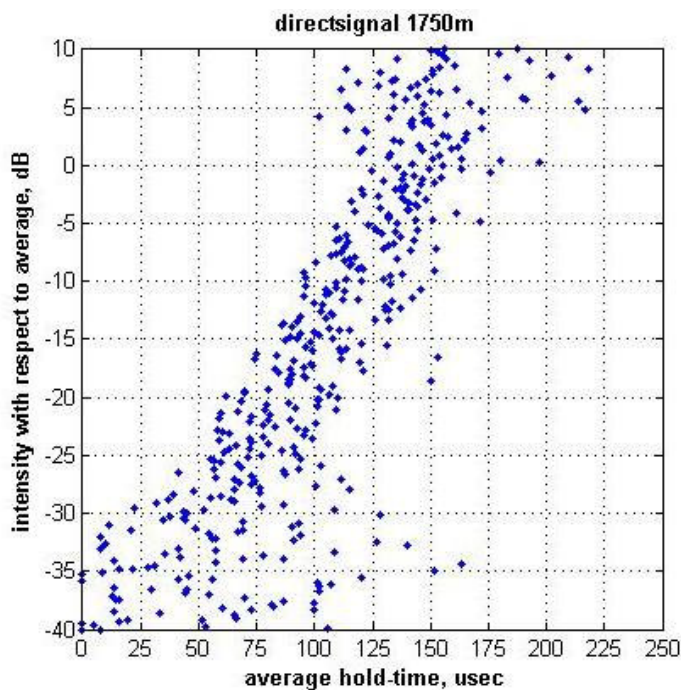

**Figure 11. Quantized signal intensity (I) vs. average hold-time $T_{avg}(I)$
for the medium-turbulence channel data**

TrellisWare's FSO channel model generator was configured with the data displayed in Figure 11 and the experiment of Section C2 was duplicated using TrellisWare FSO channel model generator. The comparison is illustrated in Figure 12. The simulated performance of the coded-protocol is summarized in Table 4.
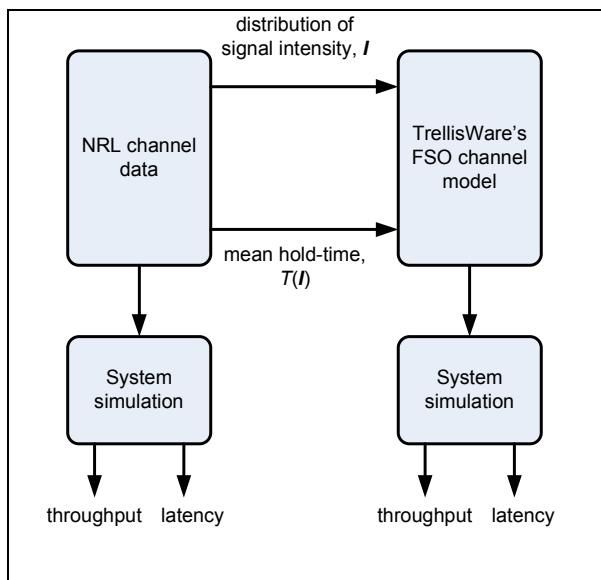
Figure 12. Generating equivalent channel models from NRL data

Table 4. Simulated performance of the coded-protocol using NRL channel data set and TrellisWare's equivalent model

	directsignal 1750m	
	NRL-data set	TrellisWare's model
Avg receive snr, dB	30	30
Throughput, Mbps	610	635
Avg latency, msec	0.3	0.2
Max latency, msec	4.4	3.9

       Table 4 displays a comparison of simulated performance figures for the two experiments shown in Figure 12. The first column of the table is reproduced from Table 2 whereas the second column lists the performance figures obtained using TrellisWare's channel models with comparable parameters. The experiment shows that TrellisWare's FSO channel models, providing computational simplicity, can be useful in predicting end-to-end performance based on the statistical characterization of scintillation induced fading.

E. Work Plan Review for Phase I Option

Table 5 displays the work plan review at the end of Phase-I Option.

Table 5. Work plan review

Task number	Description	Status
1	Begin detailed protocol design with emphasis on hardware implementation aspects. Study real-world imperfections resulting from resource limitations.	**Complete**
2	Study FSO channel data, if available, collected at the NRL's research facility. Compare with TrellisWare's FSO channel models.	**Complete**

F. References

[1]   TrellisWare Technologies, Inc., "N081-072-1109: Optimized Coding and Protocols for Free-Space Optical Communications Links," SBIR Phase I Proposal (Topic # N08-072), December, 2007.

[2]   TrellisWare Technologies, Inc., "Phase-1 Progress Report #1 for Optimized Coding and Protocols for FSO communication links", July 14, 2008

[3]   TrellisWare Technologies, Inc., "Phase-1 Progress Report #2 for Optimized Coding and Protocols for FSO communication links", Sept 15, 2008

[4]   TrellisWare Technologies, Inc., "Phase-1 Final Report for Optimized Coding and Protocols for FSO communication links", Dec 11, 2008